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ON THE VERTICAL MOMENTUM OF THE FOUNTAIN PRODUCED BY MULTI-JET VERTICAL IMPINGEMENT ON A FLAT GROUND PLANE

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20. Abstract

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Comparison has also been made with Kuhn's empirical formulas, revealing some similarity as well as differences between the two sets of formulas. Additional work needed for the development of prediction methods for lift losses is suggested.

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LIST OF SYMBOLS

d	Jet Exit Diameter
d_e	Diameter of the Equal Single Jet
$\overline{D}$	Equivalent Planform Diameter
D'	Diameter of the Bolt Line Circle
e	Distance Between Adjacent Jet Centers
h	Planform Height
h'	Height at Which the Core Lift Increment Vanishes
L	Length of a Finite Plane
ΔL_2	Lift Increment of the Fountain Core
ΔL_3	Lift Increment of the Fountain Arms
m	Index for the Fountain Width, Equation (8)
M_y	Vertical Momentum Flux (y direction)
$M_{y,L}$	Vertical Momentum Flux of a Finite Plane
$M_{y,a}$	Vertical Momentum Flux of the Fountain Arms
$M_{y,c}$	Vertical Momentum Flux of the Fountain Core
n	Index in the Fountain Velocity, Equation (7)
O	Origin of the Coordinates
O^*	Origin with Respect to the Projected Jet Center
P	Field Point
r	Distance Between O^* and P
s	Shape Factor
T	Total Thrust of the Jets
V	Velocity of the Fountain at the Plane of Symmetry
w	Fountain Width
x,y,z	Cartisian Coordinate (Figure 1)
θ	Angle (Figure 1)
Θ	Solidity Factor of Jet Curtain
λ	Index of Height Decay, equation (9)
ρ	Density

ABSTRACT

An analysis of the vertical momentum flux for the fountain produced by multi-jet vertical impingement on a flat ground plane is presented. The jets are considered to have equal thrust and the same exit diameter, and to be equally-spaced on a bolt circle. Analytical formulas for both the core and arms of the fountain have been derived, and show the dependence on the height, planform size, and number of jets. Preliminary numerical comparison with some experimental data indicates the formulas to be capable to produce acceptable predictions.

Comparison has also been made with Kuhn's empirical formulas, revealing some similarity as well as differences between the two sets of formulas. Additional work needed for the development of prediction methods for lift losses is suggested.

INTRODUCTION

In the design of V/STOL aircraft, the lift losses in the hovering flight mode of the aircraft is known to be a major problem area. At the present time, a reliable prediction method is still not available, although considerable efforts, both analytical and experimental, have been expended on the problem for many years (e.g., references 1 to 6). The method devised by Karemaa, et al. (references 2 and 4) is basically empirical, and requires for its implementation an adequate data base not yet in existence. Currently, this method is being further developed with additional experimental and analytical work at General Dynamics (Forth Worth) (reference 4, for example).

Recently, in a technical report prepared for the Naval Air Development Center, Kuhn (reference 7) presented a method for estimating the lift losses experienced by a multi-jet V/STOL aircraft hovering in ground effect. Many useful formulas for the suckdown and fountain lift increment have been obtained. This method was developed by correlating available data on flat plate and low wing configurations, and, consequently, has limited scope of applicability.

Kuhn's method and formulas, even empirical in nature, do provide some helpful insight of the problem. For example, his formula for the lift increment due to fountain core is shown to be a function of the "solidity of the jet curtain." It appears that Kuhn's method does have physical bases, although his approach is empirical.

In the present study, an attempt is made to develop an analytical approach for the aerodynamics of lift losses, and to derive analytically formulas for the lift losses by making use of some simplifying assumptions and hypotheses. As will be discussed later in this report, these assumptions or hypotheses are of a basic nature, and have some experimental evidences of validity. The work reported here will be concerned with the lift increment produced by multi-jet impingement in ground effect. The other key problem in lift losses, i.e., the suckdown, will be considered later.

TWO JET CASE - SOME BASIC CONSIDERATIONS

Figure 1 shows a sketch for two jets impinging on a flat ground plane to form a fountain (sheet) whose midplane is in the x - y plane. The two jets are assumed to have equal thrust and the same exit diameter d. The total momentum flux in the vertical direction y across a plane perpendicular to y is:

$$M_y = \rho \int_{-\infty}^{\infty} sw(V\cos\theta)^2 \, dx^* \tag{1}$$

where w is the width of the fountain, V is the velocity of fountain flow in x - y plane, and s is the shape factor.

The assumption is made that V is in the radial direction r with its origin at the point 0^* , i.e., the projected jet center. This assumption has some experimental support (see e.g., reference 5). In addition, if the momentum flux is assumed to be conserved for both the wall jets and the fountain, then

$$\rho sw\, V^2 r = C = \text{Constant} \tag{2}$$

By using the relation $dx^* = Hd\theta/\cos^2\theta$,

$$M_y = C \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \cos\theta \, d\theta = 2C \tag{3}$$

Now C can be expressed in terms of the total thrust of the two jets:

$$C = \frac{T}{2\pi} \tag{4}$$

Thus, the vertical momentum flux M_y is:

$$M_y = \frac{T}{\pi} \tag{5}$$

This expression of M_y shows no dependence on h, the height from the ground.

Next consider a finite plane of length L (figure 2). The momentum flux $M_{y,L}$ is:

$$M_{y,L} = \frac{T}{\pi}\sin\theta_o = \frac{T}{\pi}\frac{L}{\left[L^2 + (e+2H)^2\right]^{\frac{1}{2}}} \tag{6}$$

Both these expressions (5) and (6) are expected to have limited validity. It is necessary to reexamine the assumptions used in the derivation.

Hertel (reference 1) has carried out experiments to measure the velocity of the upflow in the fountain, and found that if a reflection plate was inserted at the plane of symmetry, there occurred a dramatic change in the velocity field as shown in figure 3. In the presence of the plate, the upflow velocity assumes a form characteristic of a wall jet. However, the velocity field in the fountain is evidently different from that of a wall jet.

In addition, measurements by Grumman (reference 3) for the upwash total pressure show its decay with distance to be different from that of the wall jet. A typical example is shown in figure 4. Using the jet center as the virtual origin, the decay is approximately $r^{-3.8}$, considerably more rapid than the square of the maximum velocity of a wall jet.

In figure 5, two regions are identified, i.e., the lower <u>wall jet</u> and the upper <u>fountain</u>. Consider a point $P_e(r_e, \theta)$ at the boundary of these two regions. The maximum velocity and width of the fountain at P are V_e and w_e, respectively. The maximum velocity and fountain width at a point P are assumed assumed to be: (7)

$$\left(\frac{V}{V_e}\right)^2 = \left(\frac{r_e}{r}\right)^n ; \tag{7}$$

$$\frac{w}{w_e} = \left(\frac{r}{r_e}\right)^m \tag{8}$$

The above representation for the velocity and width of the fountain is chosen for convenience. It is possible that both V and w may be found to depend on both r and θ upon further study.

Substituting the above relations into (1) yields, instead of equation (5), the following expression for M_y:

$$M_y = \frac{1}{\left(1 + \frac{2h}{e}\right)^{n-1-m}} \frac{T}{\pi} \tag{9}$$

In obtaining the above expression, it is assumed that $\rho\, s_e w_e\, V_e^2\, r_e = C =$ constant, i.e., there is no momentum loss in the wall jet, an acceptable assumption suggested by the measurements of Donaldson and Snedeker (reference 8). Equation (9) shows that the decrement in M_y is due to the momentum loss in the fountain. Evidently, the parameter $\lambda = n-1-m$ vanishes when the momentum in the fountain is conserved. As indicated already, the value of n has been estimated to be about 3.8 based on Grumman measurements. An accurate value for m is not available, but Grumman's measurements suggests that m is not high enough to make λ vanish. A reasonable value for m appears to be about 1.5. Thus, it is suggested for convenience to take λ to be one ($\lambda = 1$).

According to a personal communication, Dr. D. Kotansky (reference 9) from his measurements at MCAIR did, indeed, find strong evidences of momentum loss, which amounts to, for example, 50% of the incoming momentum flux in the x - y plane at a height of y = d in the fountain of a two jet case. However, the mechanism responsible for the loss has not yet identified precisely.

MULTI-JET VERTICAL IMPINGEMENT

Figure 6 shows a four-jet arrangement with D' as the "bolt circle" diameter. It is well known that when the number of jets is greater than 2, the fountain will be made of a core, and several arms (four arms for the four-jet arrangement). In the following, formulas for the vertical momentum flux in the fountain will be derived. A basic assumption is that all the streamlines are straight lines, and, in addition, the streamline initiating from O* and reaching the arm OC perpendicularly will be in the vertical direction y (figure 7). All the multi-jet cases considered in the present work have the jets equally spaced around the bolt circle, with the jets having equal thrust and equal exit diameter d.

The Core

At the present time, the knowledge of the fountain is not sufficient to allow an analysis without introducing additional assumption for the fountain flow. In figure 7, which shows a segment of the flow in the ground plane for N jets, two flow patterns are sketched. In (a), the portion of the wall jet segment is assumed to turn up vertically at the arc OO' to form the fountain core. On the other hand, as shown in figure 7(b), the wall jet is assumed to turn up along OC and O'C.

It follows from figure 7(a) that the vertical momentum flux of the core is:

$$(M_{y,c})_a = 2N \int_0^{\frac{\pi}{2} - \frac{\pi}{N}} d\theta = \left(\frac{1}{2} - \frac{1}{N}\right) T, \qquad (10)$$

where T is the total thrust of the N jets. If the pattern in figure 7(b) is used,

$$(M_{y,c})_b = 2NC \int_0^{\frac{\pi}{2}} \cos\theta \, d\theta = \frac{T}{\pi} \cos\left(\frac{\pi}{N}\right) \qquad (11)$$

Both the above expressions are not expected to be exact, since the models shown in figure 7(a) and (b) are highly idealized. Evidently, $(M_{y,c})_b \leq (M_{y,c})_a$ as shown in table I. It is possible that $(M_{y,c})_a$ is more accurate for larger

values of N, while $(M_{y,c})_b$ more accurate for N = 3. Future measurements may confirm the expectation that $(M_{y,c})_a$ and $(M_{y,c})_b$ are the upper and lower bounds of the core momentum flux.

The same expression $(M_{y,c})_a$ has been obtained by Kotansky and Glaze (reference 6). They also found out the actual values to be less by a factor of one third to one quarter.

Using the same approximation for the momentum loss in the fountain as in the two jet case, the following expression for $M_{y,c}$ can be obtained and will be used for further study in this work:

$$M_{y,c} = \frac{T}{\pi(1+2h/e)} \cos \frac{\pi}{N} \tag{12}$$

The above expression vanishes when N = 2, the two jet case.

The Fountain Arms

Based on the above approximations, the following formula for the vertical momentum flux for N jets is obtained for arms extending to a radial distance $\bar{D}/2$ from the fountain axis. $\bar{D}$ may be regarded as equivalent to the mean "planform diameter" used in Kuhn's study (reference 7).

$$M_{y,a} = \frac{T}{\pi} \frac{\bar{D}}{(1+\frac{2h}{e}) \left[\bar{D}^2+(2h+e)^2\right]^{\frac{1}{2}}} \tag{13}$$

Note that the geometrical quantities e and D' are related to N by:

$$\frac{e}{D'} = (1-\cos^2 \frac{\pi}{N})^{\frac{1}{2}} \tag{14}$$

The dimensionless parameters for the N jet configuration are:

$$\begin{aligned} &N - \text{Number of jets} \\ &\frac{D'}{\bar{D}} - \text{Planform Size} \\ &\frac{h}{\bar{D}} - \text{Height} \end{aligned} \tag{15}$$

Note no actual planform is assumed to be present in the analysis. Otherwise, suckdown effect has to be considered.

It might be expected that the ratio of the distance (e) between two adjacent jets and the jet exit diameter (d) should appear as a separate parameter in the above expressions for the momentum flux. That it does not suggests their validity to be limited to values of e/d within a certain range. The lower limit is likely to be 3, but the upper limited remains to be determined.

COMPARISON WITH KUHN'S WORK

Kuhn's formulas for the lift increment are as follows:

<u>Core</u>

$$\frac{\Delta L_2}{T} = .135\ N^2 \Theta \left(\frac{h'}{\bar{D}} - \frac{h}{\bar{D}}\right) \tag{16}$$

$$\frac{h'}{\bar{D}} = 1.22 \frac{1}{N} \left(\frac{D'}{d_e}\right)^{.65} \tag{17}$$

<u>Arms</u>

$$\frac{\Delta L_3}{T} = 10^{(.9-10h/\bar{D})} \tag{18}$$

The core lift increment is to be taken to be zero when $N = 2$. The expression (12), of course, vanishes automatically at $N = 2$. The quantity h' is the height at which the core lift increment becomes zero. Since the jet merging is not included in the present analysis, prediction of this height is beyond its scope. d_e in equation (17) is the diameter of "equivalent single jet", and is equal to $N^{\frac{1}{2}}d$ for circular jet exit with diameter d. Θ is the fraction of jet pattern circumference blocked by individual jets, and can be taken as $\pi D'/N$. Thus, equation (16) can be written as:

$$\frac{\Delta L_2}{T} = .135\,\pi\, D' N \left(\frac{h' - h}{\bar{D}}\right) \tag{19}$$

Due to the difference in approaches, it is difficult to make comparison analytically the expressions (12) and (13) with Kuhn's (16) and (18). There is some similarity between (12) and (19) for the core. For the arms, while equation (13) is dependent on the parameters N, $d'/\bar{D}$ and $h/\bar{D}$, Kuhn's expression (18) is a function of $h/\bar{D}$ only. The numerical values obtained from (13) are generally much higher than those from (18). It is of interest to note that except $h'/\bar{D}$ Kuhn's formulas do not have the jet exit diameter d as a parameter.

The numerical results for the total momentum flux $M_y = M_{y,c} + M_{y,a}$ for the case whose lift increments have been reported in reference 4 is shown in figure 8. The case is a four-jet configuration with $D'/\bar{D} = 0.7$. Figure 8 shows the comparison between the calculated results for M_y based on equations (12) and (13), and the experimental results from reference 4. The agreement between the calculated and experimental results cannot be considered as entirely satisfactory, but appears to be adequate to support the validity of the method of approach used in the present analysis.

Kuhn also showed other experimental results including some cases for which the lift increment vanishes at h'. The case chosen for comparison for the present analysis does not exhibit this behavior.

CONCLUDING REMARKS

An analysis of the vertical momentum flux for the fountain produced by multi-jet vertical impingement on a flat ground plane is presented. The purpose of the analysis, which is based on several aerodynamic approximations and hypotheses, is primarily to establish the physical bases for a rational prediction method for the lift losses of V/STOL aircraft in hovering flight in ground effect. Analytical formulas for both the core and arms of the fountain have been derived, and show the dependence on the height, platform size, number of jets, and others. Preliminary numerical results and comparison with some experimental data indicate these formulas as capable to produce acceptable qualitative predictions.

Comparison has also been made with Kuhn's recently developed empirical formulas for the lift increment produced by fountain. Although obvious differences exist between these two sets of formulas, some similarity is apparent suggesting that Kuhn's method does have valid physical bases. Further development of prediction methods for lift losses requires not only analytical work but also careful and basic experimental work to verify assumptions and hypotheses used in the analysis and to improve our understanding of the aerodynamic phenomena involved. In particular, for the lift increment problem, the details of the fountain formation, and the aerodynamic structure, including the momentum loss, of the fountain should be studied to provide information needed for the development of prediction methods, either analytical or empirical.

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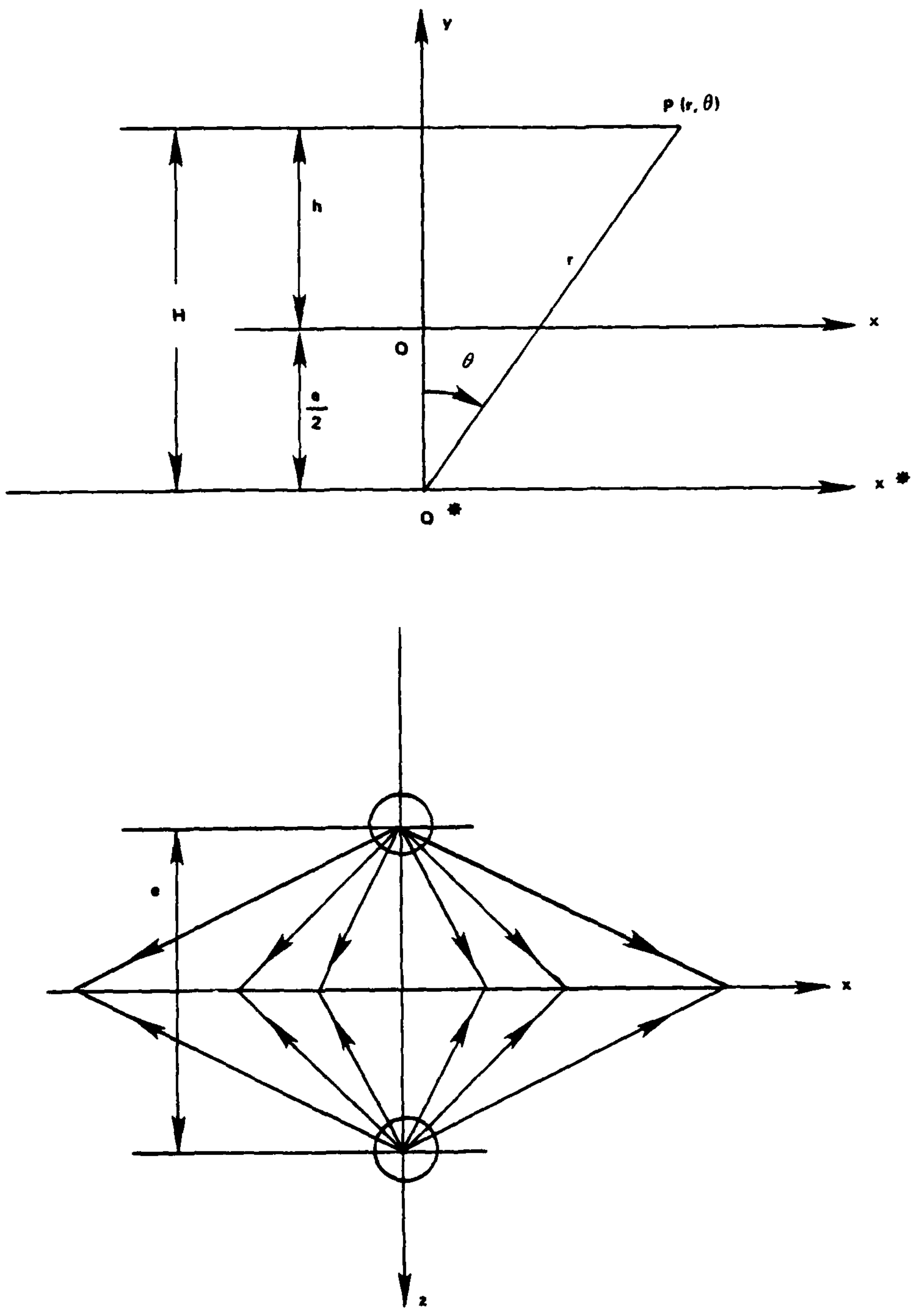

FIGURE 1 - Two-Jet Implingement Problem.

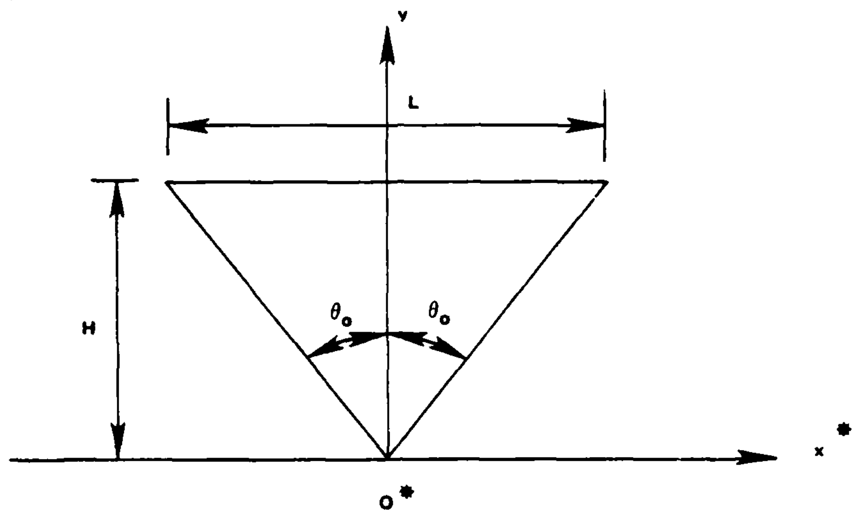

FIGURE 2 - Finite Plane of Length L.

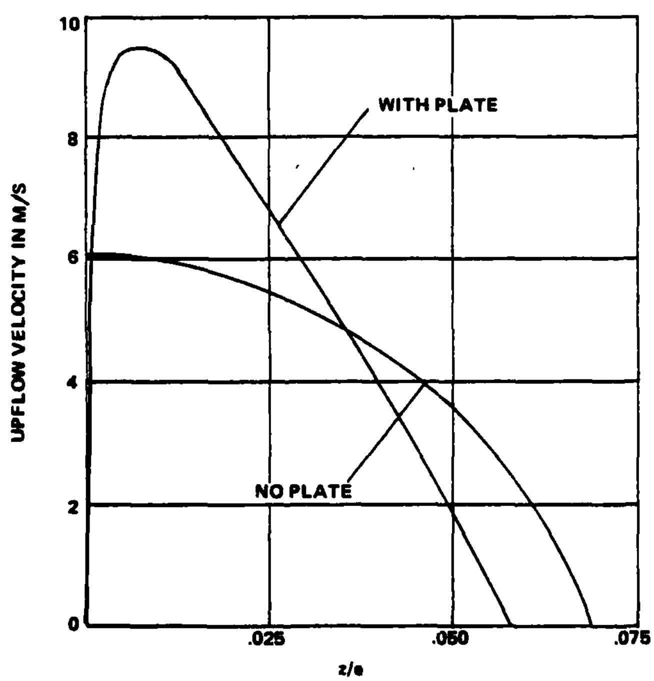

FIGURE 3 - Effect of a Reflection Plate on the Upflow. Two Equal Jets.

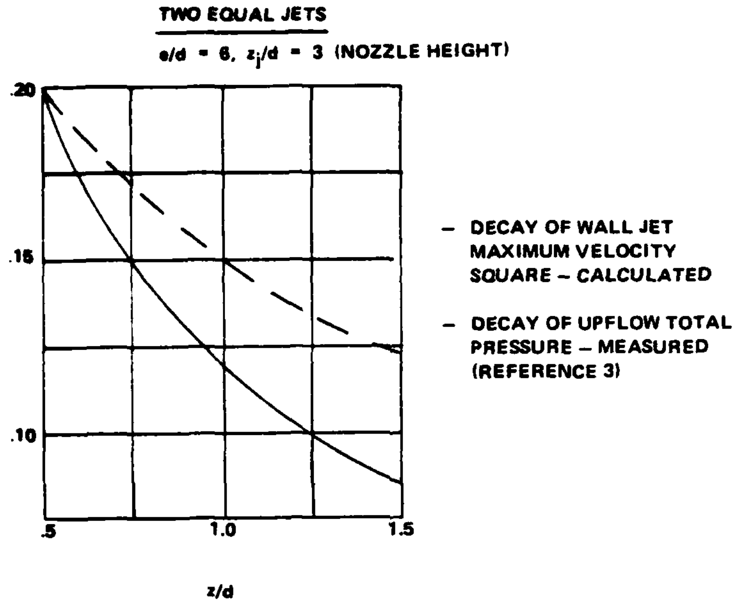

FIGURE 4 - Comparison of Decay Rates.

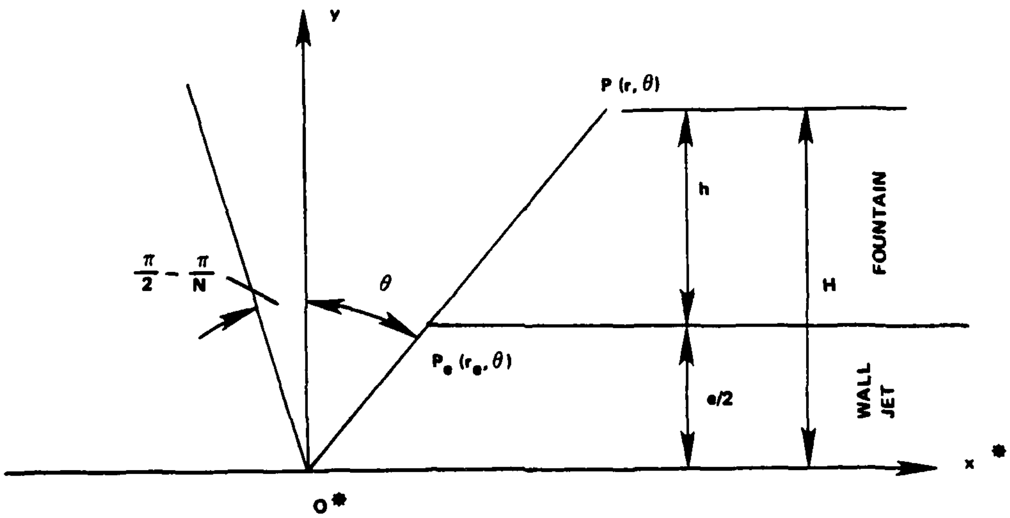

FIGURE 5 - Flow Regions and Coordinates

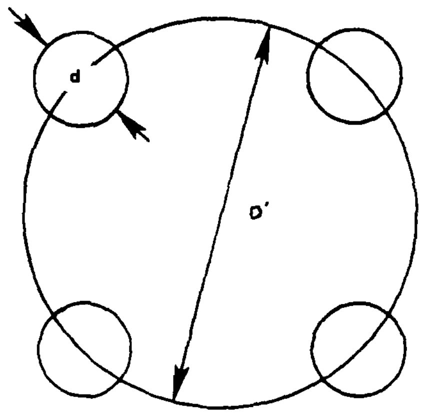

FIGURE 6 - Four Equal Jets. D'-Bolt Circle Diameter.

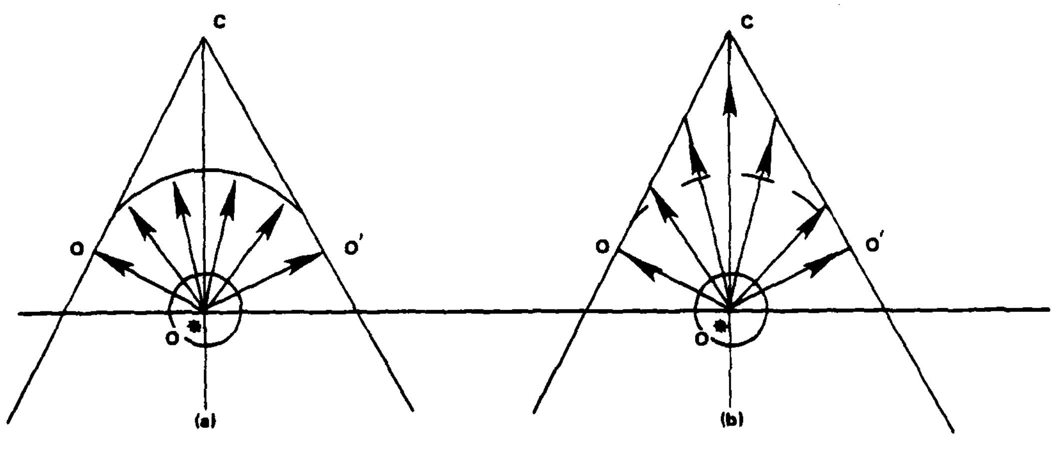

FIGURE 7 - Two Models for Fountain Core.

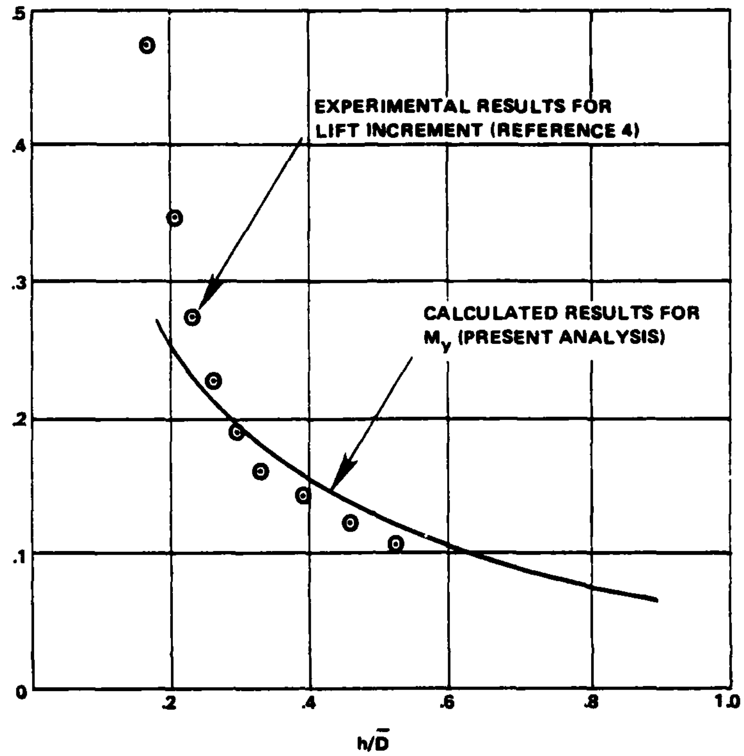

FIGURE 8 - Lift Increment and Vertical Momentum Flux M_y. Four Jets. $D'/\bar{D}=0.7$.

Table I - Numerical Values for the Momentum Flux

N	$(M_{y,c})_a$	$(M_{y,c})_b$
2	0	0
3	$\frac{1}{6}$	$\frac{1}{2\pi}$
4	$\frac{1}{4}$	$\frac{2}{2\pi}$
6	$\frac{1}{3}$	$\frac{\sqrt{3}}{2\pi}$
∞	$\frac{1}{2}$	$\frac{1}{\pi}$

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